

ON THE DESIGN OF WALKING MACHINES USING BIARTICULATE ACTUATORS¹

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Biarticulate muscles – muscles that span more than one joint – are ubiquitous in nature and are believed to play an important role in locomotion. In particular, biarticulate muscles may be important during running and jumping tasks; tasks at which most current bipedal robots are deficient. In human, it is known that biarticulate muscles greatly assist in transferring energy from muscles near the body (i.e. thigh muscles) to muscles far away (i.e. ankle muscles). Here we reproduce this effect in a robot leg design based on the muscle architecture of the human leg, including biarticulate muscles. We demonstrate that biarticulate muscles can transfer a significant amount of work and power from upper limb segments. Further, we show that peak power transfer is dependent on the exact timing between biarticulate muscles and the monoarticulate muscles that they assist. We show analytically that the pull-but-not-push property of muscles is critical to ensure only positive work transfer from upper limbs to lower limbs.

1 Introduction

The human body has 244 kinematic degrees of freedom (DOF) controlled by a minimum of 630 muscles: the muscle to DOF ratio is about 2.6:1 [1]. Since human muscle is only capable of pulling not pushing, moving a joint requires a minimum of two muscles (actuators) per joint. Thus, the minimum muscle/actuator to joint ratio is 2:1; the human body has many more muscles than the minimum required.

Many muscles in the human body are *biarticulate*— muscles that span more than one joint. These muscles operate in tandem

* This work was supported by a generous startup grant to MAL from the College of Engineering, University of Arizona.

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with monoarticulate muscles. Perhaps the most studied biarticulate muscle is the gastrocnemius muscle (GA). This muscle attaches to the femur (the thigh bone) and the back of the heel as one of the muscles acting on the ankle joint. See Fig. 1. Thus, the GA spans two joints, the knee and the ankle. The GA muscle is assisted by the soleus (SO) and is opposed by the tibialis anterior (TA), both acting around the ankle alone. The ankle has one more major muscle than is needed in pitch.

The GA assists in transmitting power from the thigh to the ankle. As the knee is rotated, the GA can allow the muscles acting on the knee to do work on the ankle. The knee is extended by the muscles including the rectus femoris (RF), itself a biarticulate muscle anchored to the hip and knee and the vastus lateralis (VA) acting on the femur and knee. Finally, the Gluteus Maximus (GM), assists in extended the hip femur. This leads to chain of energy transfer:

Gluteus Maximus->Rectus Femoris-> Gastrocnemius-> Ankle

Power transmission and shock absorption via biarticulate muscles has been documented in humans [2]. While these properties are remarkable, biarticulate muscles are not used in walking machines, with at least one exception [3].

Many attempts have been made to produce human-like walking in robots, the most famous example being Honda's 'Asimo' [4]. However, human and animal speed and flexibility (i.e. running, jumping, and balancing) surpasses anything produced artificially thus far. Asimo, remarkable as it is, can demonstrate only a small fraction of human locomotor capability.

Most walking robots use rotational motors at the joints to control movement, while the concept of biarticulate muscles has been neglected in the robotics literature (a notable exception being [5]). Undoubtedly, this is partially due to need to minimize the number of actuators in a robot to reduce weight and increase system reliability. However, with widely available smart actuators, for example Animatics (<http://www.animatics.com>) and Robotis (<http://www.robotis.com>), highly reliable modular actuators are

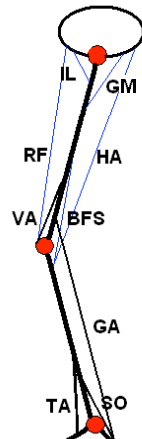


Figure 1. Model of the human leg. TA is tibialis anterior, SO is soleus, GA is gastrocnemius, VA is Vastus lateralis, RF is rectus femoris, BFS is short head of biceps femoris, HA is two-joint hamstrings, GM is gluteus maximus, and IL is iliacus. Redrawn from [1].

readily available. We anticipate the movement toward high DOF systems will accelerate.

In this article, we describe theory behind biarticulate robots, and an implementation in a robotic leg. We then report on development of methodology for measuring work transference and demonstrate the use of this methodology in a real robot. We show energy flowing via the GA, and show that the timing of SO versus GA activation is important for achieving maximum power output at the ankle. We demonstrate analytically how power is transferred from the

RF and VA to the ankle.

2 Mammalian leg muscle architecture

The human leg can be modeled as a system of three parallel joints (hip, knee, and ankle) and nine muscle actuators, see Fig. 1. The muscles include three biarticulate muscles: the GA, which spans the knee and ankle, the RF, and the HA, which both span the hip and knee. The leg uses an agonist/antagonist, or flexor/extensor design with regard to monoarticulate muscles. Extensor muscles are used to support the body weight of the robot against gravity. Flexor muscles are used to lift the limb. The flexor muscles are generally much smaller than the extensor muscles.

Monoarticulate muscles on the ankle include the TA, which flexes the foot, and the SO, which in conjunction with the GA, extends the foot. The VA extends the knee, while the BFS helps

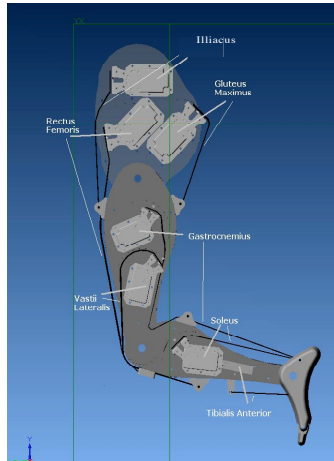


Figure 2. Actuator architecture of robot leg. Shown above is a cut away view of the robot limb. High performance modular motors pull on Kevlar straps to activate the joints. Biarticulate actuators are: Gastrocnemius and Rectus Femoris. Hamstrings are not implemented here.

flex the knee. The GM holds the hip upright, while the Iliacus (IL) flexes the hip.

In human beings it has been demonstrated that knee extensors generate significantly more force than the knee flexor [6]. An even more dramatic example, which the reader can verify, is of the ankle flexor versus extensor.

In human, the cross sectional area (CSA) of various muscles have been measured. While the particular configuration of the muscle (e.g. pennation angle) can affect the force generating capability of muscle, we note that

muscles such as the VA and SO have a much greater CSA than muscles such as biarticulate GA and RF [7]. This implies that the monoarticulate extensor muscles must produce more force. Moreover it suggests that implementation of a robot based on human leg muscle architecture can be done using smaller motors for the flexor and biarticulate muscles, thus reducing the weight penalty for using multiple motors for each joint.

3 Implementation of Design Concepts

We implemented these ideas in an human-like leg, with pin joints at the hips, knees and ankles. Each joint is actuated by a combination of actuators designed to mimic the mechanics of muscles. The following muscles were modeled: GA, TA, SO, VA, RF, IL and GM (the HA and BFS were not modeled).

The toe was modeled as a passive joint. An elastic cord is used to straighten the toe. The use of a toe allows natural walking

motion. The distances and proportions of the limb segments were based on human anthropometric data [7].

3.1. *Actuators*

The actuators were composed of stiff Kevlar strap connected to a motor. The straps were affixed to a mounting bracket that pulls and releases the strap in one direction. We have selected Robotis RX-28 motors for the combination of force and compactness for the GA, SO and VA muscles and a Futaba S3150 for the TA muscle. Robotis RX-64 are used for the HS, RF and IL.

We used an agonist/antagonist muscle configuration. This type of actuation allows the motor to pull but not push, similar to muscle action. As an example, we modeled the TA with one motor placed in the calf and connected by a Kevlar flat strap from it to the front of the foot. The SO was modeled by connecting a flat strap between the rear of the foot and the calf. The dual strap also permit joints to be "stiffened" by applying force to both sides, which assists in leg stabilization during foot touch down.

Figure 2 shows a 3D CAD drawing of the leg design, including motor positions and Kevlar straps running down the front and back of the leg. Figure 3 shows photos of the completed leg as constructed.

3.2. *Sensors*

Angle sensing pots (Murata SV01A103) are used to measure joint angles of the foot, knee and hip. Each sensor was calibrated in radians by comparing the voltage output versus a known angular reference. We found the pots to be highly linear. At the attachment point of the straps with the motors, we designed a custom made force sensor. This sensor is based on a Futek FSH01463 Force gage. The assembly was mounted between the motor bracket and the strap. As force is exerted by the strap, this force is measured by the gage. Finally, we used a load cell to measure tension at the Achilles' tendon (both the SO and GA act on the ankle via the Achilles' tendon). The model number of the Achilles' tendon load cell was unknown.

4 Measuring work and peak power at the ankle of the robot

4.1. Work Transfer

Work produced by a rotational torque can be written in time-discrete form as:

$$W = \sum \bar{\tau} * \Delta \bar{\theta}$$

The torque at the ankle is given by:

$$\tau_{Ankle} = -\tau_{TA} - \tau_{GN} - \tau_{SO}$$

where $\tau_{TA}, \tau_{GN}, \tau_{SO}$ are torques produced by the TA,GN and SO respectively. Multiplying by the angular displacement, in radians, of the joint we have the net work at the ankle:

$$\begin{aligned} W_{Ankle} &= \Delta \theta_{Ankle} \tau_{Ankle} = -\Delta \theta_{Ankle} \tau_{TA} + \Delta \theta_{Ankle} \tau_{GN} + \Delta \theta_{Ankle} \tau_{SO} \\ W_{Ankle} &= -W_{TA} + W_{GN} + W_{SO} \end{aligned}$$

where W_{TA}, W_{SO}, W_{GN} is the work contribution by the TA,SO and GN respectively.

Likewise, for the knee:

$$W_{Knee} = W_{VL} + W_{RF} - W_{GN} - W_{BFS} - W_{HA}$$

In the simplified case of activating the extensors alone:

$$\begin{aligned} W_{Ankle} &= W_{GN} + W_{SO} \\ W_{GN} &= W_{VL} + W_{RF} - W_{Knee} \end{aligned}$$

Substituting:

$$W_{Ankle} = W_{SO} + W_{VL} + W_{RF} - W_{Knee}$$

Because muscles pull, but cannot push we note $W_{SO} \geq 0$, $W_{GN} \geq 0$ and thus $W_{VL} + W_{RF} - W_{Knee} \geq 0$. Hence the work contribution of the upper leg and the lower limb sum together when the GA is active; the work done on the ankle is greater than just the SO alone. We conclude that the work done at the ankle on the environment is assisted by the RF and the VA.

Note, it is critical that an actuator be cable of pulling *and not pushing*. If the GA could push, it would be possible for the upper leg to take energy *away* from the ankle. Thus, a stiff rod connection between actuator and joint cannot be used, for example, if we are to adhere to biological principles.

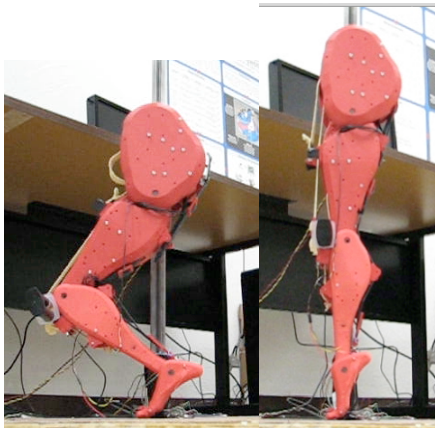


Figure 3. Bent knee squat. This configuration was used to measure the contribution of SO and GA to the ankle power as well as to analyze the effect of SO and GA activation timing on peak power production.

4.2. Methods

During the following experiments, the robot was commanded to do a weight lifter's 'squat.' The timing of the SO versus GN was varied as was the activation of the SO or GN. Simultaneous measurements were made of the potentiometer and the force gage using a PICO Scope (Model 5203). The sampling rate was 100K Hz. To improve

differentiation, data was decimated to sampling rate of 100 Hz.

The data was smoothed using a alpha tracker ($\alpha = 0.2$). The raw angle and force signals were converted to radians and Newtons using a linear calibration equation. Time and angle difference were computed.

Next the change in distance at the ankle attachment point was computed using the following formula: $\Delta x = r * \Delta \theta$ where r is the moment arm from the ankle rotation axis to the ankle attachment point of the Achilles' tendon in units meters (0.0023 meters) and θ is the angular measurement of the ankle in radians.

Combining the displacement in meters and force in Newtons we can integrate the measurement to compute work. Power is the time derivative of work. We can compute the instantaneous power at the ankle by: $P = \frac{\Delta x}{\Delta T} * F$

4.3. Experiments

In the following experiments, the robot was constrained by a vertical rod to control balance. We confirmed that measurement of the work done at the ankle reflected the actual work. This was done

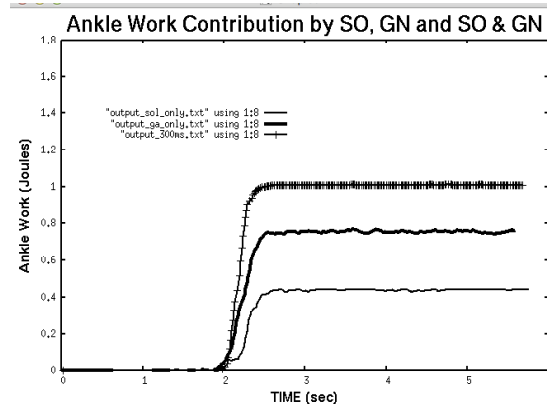


Figure 4. Ankle work done by SO, GA and both SO and GA together during return from squat.

by elevating the center of mass of the robot during a calf-raise movement. In particular, we calculated work done at the ankle as 0.433 Joules and the work done by elevating the center of mass as 0.41 joules, the difference being about 4%.

4.3.1 Contributions of SO and GA to ankle work and power

Experiment 1 examined the work and power output of the ankle from a bent knee squat. The starting configuration of the robot was toes directly under the hip (Fig. 3a). The robot was then command to extend fully from a squat (Fig 3b). We varied the following conditions: (1) SO activation, GA relaxed, (2) GA activation, SO relaxed, (3) Both activated together. We then computed both work versus time and power versus time.

In Figure 4 we see that more work is done in the ankle when both SO and GA are activated versus when either SO or GA is activated alone. Further, we note that the GA delivers more power to the ankle than the SO. In this particular experiment, we use a delay between the GA activation and SO activation of 300 ms. In figure 5 we see that peak power for GA+SO is greater than either alone.

by calculating total work in two ways: (1) By the ankle torque method described above and by calculation of the work done by

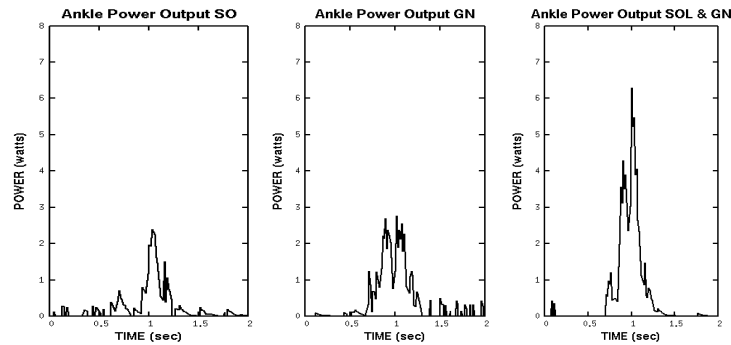


Figure 5. Power versus time at ankle during return from squat. (A) SO alone, (B) GA alone (C) Sol and GA.

4.3.2 Variation in Timing of SO Activation and GA activation

The relative timing of the SO and GA activation in humans has been measured and it was found that the GA activation preceded SO activation [7, 8]. We compared the case of both SO and GA activation with SO activation at the following delays: 0ms, 50ms, 100ms, 150ms, 200ms, 250ms, 300ms 350ms 450ms.

Similar to experiment 1, in experiment 2 we computed the work and power done at the hip. We summarize these results by showing the peak work and peak power versus GA-SO delay.

Figure 6 shows the results. As can be seen, at no delay, the

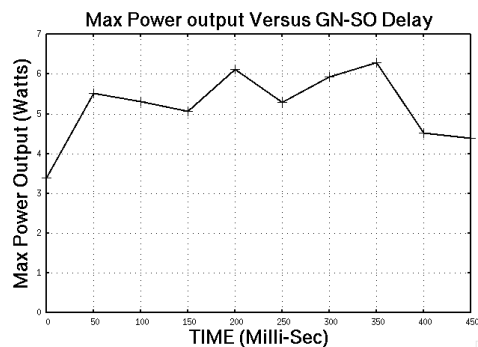


Figure 6. Max power at ankle versus delay between GA activation and SO activation.

peak power output is 3.4 watts. At 350ms the peak output rises to 6.1 watts an 80% increase in power.

We also analyzed the total work done under each delay. We found that

variation seemed insignificant. The peak work may have declined about (approximately 10%) at greater delays. In future work we will try to determine if this effect is meaningful.

5 Conclusions

Redundant biarticulate muscles are an essential part of biological walking systems. We have presented preliminary work in the construction of a lower limb that exploits the use of biarticulate muscles. We showed that the upper leg should contribute to ankle work and peak power. Through experimentation we confirmed this results. We also observed that in humans, the activation of the SO is significantly delayed from the activation of the GA. We found in our robot that a delay of 350 ms yielded a higher peak power output. Finally, we demonstrated analytically that the upper limb can add but not subtract power from the ankle.

Acknowledgments

We thank Chistoph Dribusch and Kiwon Sohn for there assistance in robot design and preparation of this manuscript.

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